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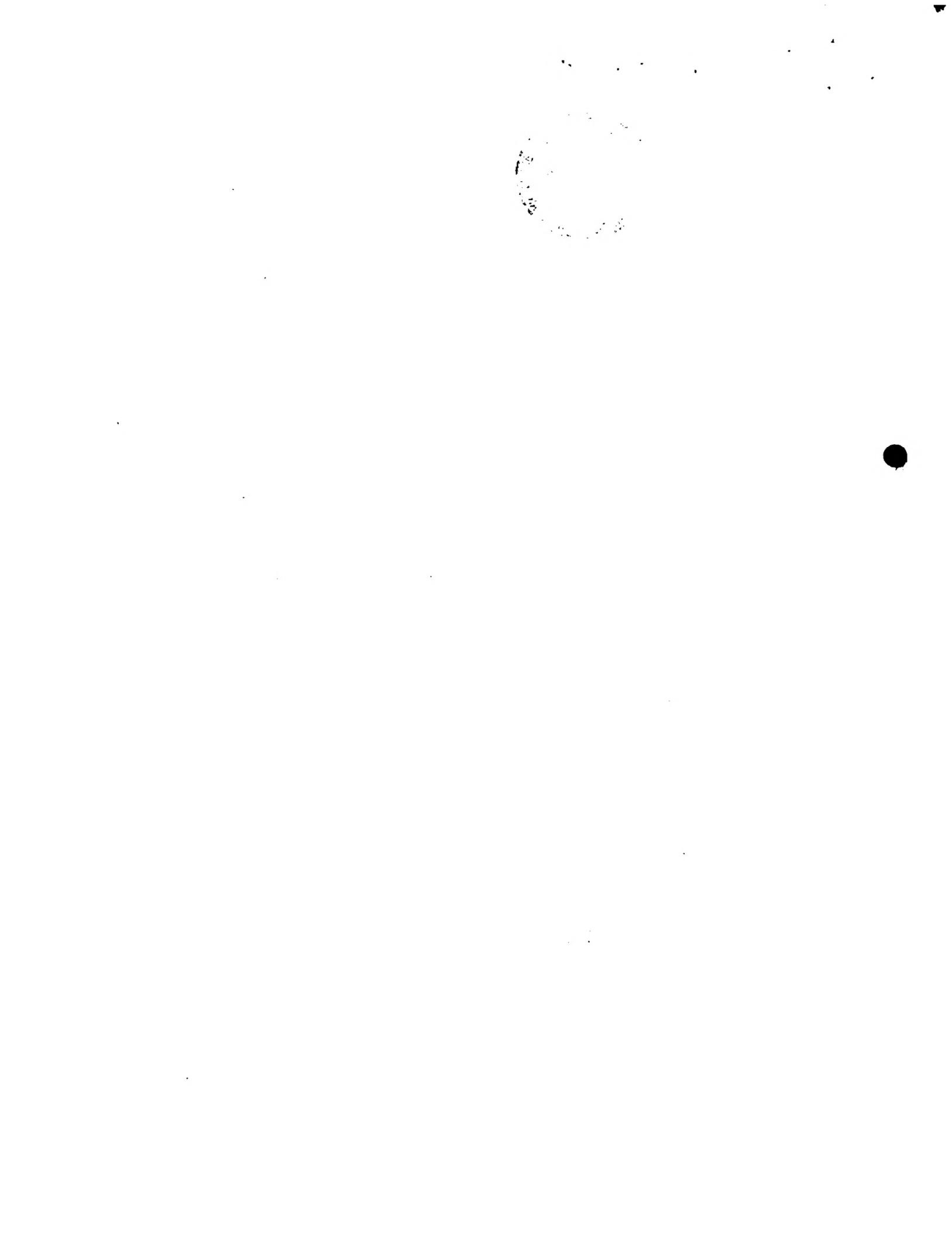
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Der Präsident des Europäischen Patentamts;  
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For the President of the European Patent Office  
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**Sheet 2 of the certificate**  
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Anmelder:  
Applicant(s):

Demandeur(s):

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

75007 Paris

FRANCE

INSTITUT NATIONAL DE LA SANTE ET DE LA RECHERCHE MEDICALE (INSERM)

75654 Paris Cédex 13

FRANCE

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Adenovirus vectors for the transfer foreign genes into cells of the central nervous system,  
particularly in brain

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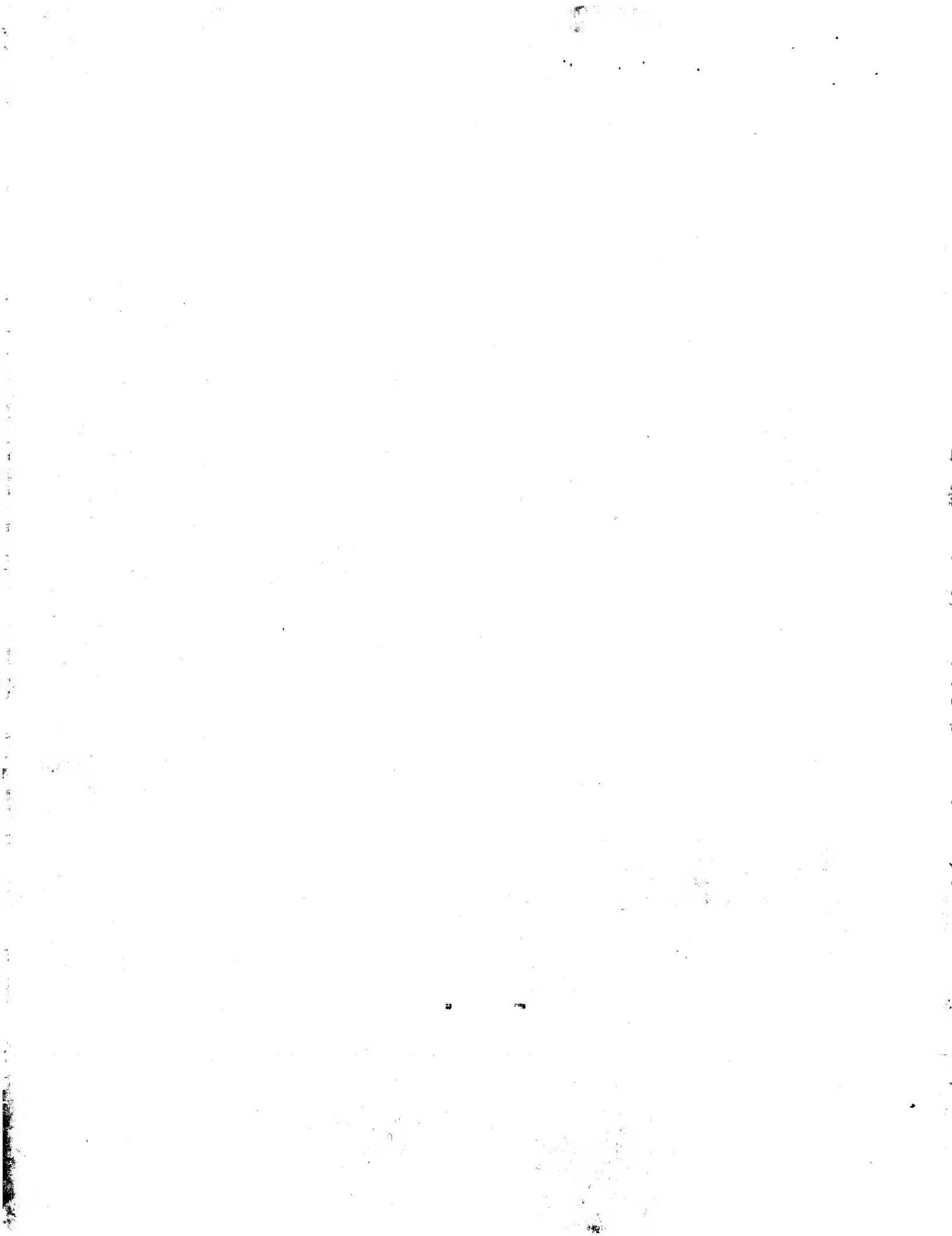
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**ADENOVIRUS VECTORS FOR THE TRANSFER FOREIGN GENES INTO  
CELLS OF THE CENTRAL NERVOUS SYSTEM, PARTICULARLY IN  
BRAIN**

To transfer safely and efficiently therapeutic DNA into the central nervous system, is a formidable challenge in the development of active therapies in brain diseases.

Preliminary investigations have been carried out with a number of vectors, more particularly retroviral vectors and herpes simplex derived vectors. However the usefulness of such gene transfer vehicles has, to date, been limited.

In most cases, retroviral vectors are not useful because they are unable to infect postmitotic cells, including most neural cells(1). Herpes simplex derived vectors infect neural cells but problems of pathogenicity and of stability of gene expression remain unsolved(2,3). In addition Herpes simplex derived vectors have so far proven to have but limited efficacy of expression. In a most recent article (4) the authors refer to the short-term expression reported earlier of HSV-1 derived vectors, because most of the promoters used had only been active during the acute phase of viral infection (less than 10 days post-infection). They disclosed the expression of a  $\beta$ -glucuronidase gene in a cell of the central nervous system under the control of the LAT promoter normally associated with the latency-associated-transcript (LAT) sequence of the virus. But the authors also report that, even though their experiments demonstrated the feasibility of using the LAT promoter for long-term expression of foreign genes in cells of the central nervous system to correct a genetic enzymatic deficiency in infected cells, too few cells had been

corrected to alter the disease phenotype. Consequently their vector system needed to be improved to correct sufficient cells for obtaining a clinically significant effect.

The invention aims at obviating such difficulties and at providing most effective vector systems capable of delivering foreign genes and, where appropriate, their transcription products or expression products directly to cells of the central nervous system, particularly to terminally differentiated cells, incapable of proliferation. A more particular object of the invention is also to allow for the wide spreading of such vector systems throughout the neural tissue to be infected, yet while remaining substantially confined thereto.

Still another object of the invention is to produce such vector systems which are sufficiently safe to allow for a study and regulation in vitro of cloned genes in such cells or in test animals, and for therapy, in man or animal, involving the in situ production of a selected expression product, including gene therapy.

The invention is based on the recognition that adenovirus-derived vectors, particularly non-replicative adenovirus vectors, are capable of fulfilling these aims, both in vitro and in vivo. They provide powerful delivery systems of genes into the cells of the central nervous system, more particularly brain cells. They are characterized by a degree of infectivity of sufficient magnitude to allow for the infection of considerable populations of cells. The biological experiments disclosed hereafter demonstrate the capability of adenovirus derived vectors (or adenoviral vectors) of efficiently infecting nerve cells, particularly neurons, both in vitro and in vivo.

Thus the invention provides a process for the production of a recombinant vector useful in a method comprising causing the transcription product or the expression product of a nucleotide sequence coding for a selected polypeptide to be targeted or produced in cells of the central nervous system, e.g. brain cells, particularly neural, glial or ependymal cells, wherein said recombinant vector is an adenoviral vector which comprises at least part of the genome of an adenovirus including those regions of that genome which provide the genetic information required by that adenovirus to penetrate into cells normally infectable by it, said nucleotide sequence being inserted in said genome part, under the control of a promoter either present or also inserted within said adenoviral vector, and said promoter being operative in said cells.

Thus the invention is more particularly related to the use of an adenovirus-derived vector for the expression of a selected nucleotide in the cells of the central nervous system.

The invention also provides a recombinant DNA vector characterized in that it is capable of directing the expression and/or transcription of a selected nucleotide sequence in the cells of the central nervous system and in that it comprises (i) at least part of the genome of an adenovirus, including the regions required for that adenovirus to penetrate into the cells of the central nervous system, and (ii) said selected nucleotide sequence under the control of a promoter operative in said cells.

The powerful capability of adenoviral vectors of transferring gene fragments in vivo into quiescent neural cells is illustrated by the experimental models reported hereafter, which were carried out with an adenovirus vector carrying the E. Coli lac Z gene, in neural cells of adult rats. A large number of neural

cells (including neurons, astrocytes, microglia and ependymal cells) expressed this transgene at least 60 days after inoculation of various brain areas. Injecting up to  $3 \times 10^5$  pfu in  $10\mu\text{l}$  did not result in any detectable cytopathic effects, which were only observed for the highest titers of infection ( $>10^7$  pfu/ $10\mu\text{l}$ ) and were most likely associated with a massive endocytosis of viral particles in neural cells close to the injection site.

Moreover the genomes of adenoviruses can be manipulated to accommodate foreign genes of 7.5 kb in length or more. It has a large host range, a low pathogenicity in man, and high titers of the virus can be obtained(5).

It will be readily appreciated that these results strongly support the presumption that adenovirus offers, as a vector, a new and remarkable tool to genetically modify quiescent cells of the nervous system, because of its great efficacy of infection, long term expression, wide host range and low toxicity. Thus, adenovirus should be instrumental in the study of the function of cloned gene products in their physiological and anatomical context. The ability to infect the hippocampus (as this will be shown later) is of great interest to study integrated phenomena such as long-term potentiation, in animals.

Moreover the adenovirus clearly appears as a promising means to transfer foreign genes into the brain with a therapeutic goal. Adenovirus vectors have great potential for gene therapy of nervous system diseases, such as the local delivery of growth factors or neurotransmitters for degenerative diseases and, more generally, to replace defective genes in appropriate cells. Relatively low titers of adenovirus vectors can efficiently transfer foreign genes into a significant number of brain cells without triggering

pathological effects. Subject to optimization of the doses of recombinant adenoviral vectors containing a foreign gene to be delivered into brain cells, they open new avenues in the treatment of many genetic and acquired neurological diseases, consequently an alternative to drug treatment or brain transplantation of fetal tissues.

Adenoviruses, particularly adenoviruses of type 2 or 5 (Ad2 or Ad5) are particularly preferred. They are relatively stable, can be cultured easily and rapidly (viral cycle of about 30 hours) and provide high titers : up to 10<sup>4</sup>-10<sup>5</sup> plaque forming units (p.f.u.) per infected cell. They are not oncogenic. The complete sequence of their viral genome has been established (6) and its molecular biology has been studied extensively. Finally several mutants, particularly deletion mutants, have been obtained, which makes it possible to insert fragments of large size therein (7).

Preferably the recombinant vectors for use in this invention are defective adenoviruses, whose genomes no longer contain those nucleotides sequences required for the virus replication in cells (other than brain cells) normally infectable by it. More particularly, they are free of the E1 region, including the early E1a region which activates the other early transcription units of the virus required for its replication as well as the region E1b involved in the establishment of a fully transformed phenotype, in the protection of DNA sequences during viral infection and required for the normal progression of viral events late in infection.

Preferably too, they are devoid of the E3 region which is involved in cellular immunity in vivo and is totally dispensable for growth in vitro.

Preferably however the recombinant vector for use in that invention comprises all of the sequences that are essential for the adenovirus encapsidation.

The promoter controlling the sequence coding for the selected polypeptide to be targeted or produced in the cells of the central nervous system, can either be endogenous or exogenous with respect to the adenoviral parts of the recombinant vector.

A preferred homologous promoter is any one that is likely to be recognized by the polymerases, practically RNA polymerase II, of human or animal cells infected by such adenoviruses. A particularly preferred endogenous promoter is the major late strong promoter (MLP) of the human adenovirus of type 2 (Levrero et al., 1991)(8). Another promoter that may be used consists of the early promoter of the E1a region of the adenovirus. In that last instance, a preferred defective adenovirus is devoid of its 5' region normally upstream for that early promoter. In that last instance, the nucleotide sequence sought to be introduced in the neural cells is substituted for the E1a region.

The endogenous promoters of the adenoviruses can also be replaced by other ubiquitary promoters of heterologous or exogenous origin, e.g. :

- a promoter contained in the LTR (Long Terminal Repeat) of the Rous Sarcome Virus (RSV) or the LAT promoter referred to above,
- a promoter of the IE gene of Cytomegalovirus (CMV),
- inducible MMTV promoters (originating from the mouse mammary tumor virus) or metallothioneine promoters.

Other promoters can be used to. Particularly neural or glial promoters will be preferred, particularly in instances where the nucleotide

sequence inserted in the adenoviral vector is to be targeted more specifically on more specific classes of neural cells. Reference is for instance made to the following promoters, particularly those involved in the genes coding for neurotransmitter synthesizing enzymes:

TH (tyrosine hydroxylase)  
CHAT (choline acetyl transferase)  
TPH (tryptophane hydroxylase)  
GFAP (glial fibrillary acidic protein)  
enolase  $\gamma$  (neuronal protein marker)  
aldolase C.

The invention relates also to a process for making such recombinant vectors, which process comprises inserting the nucleotide sequence whose expression is sought in the starting vectors and the transformation of infectable cells with said vectors. Where the vector is a full live virus, the recombinant viruses are then recovered from the cell culture medium. Where the recombinant vector is a defective virus, a preferred process then comprises the transformation of a transformable eucaryotic cell line (preferably of human or animal origin) which itself comprises a distinct nucleotide sequence capable of complementing the part of the adenovirus genome that is essential for its replication and which is not present in said vector, whereby that complementation sequence is preferably incorporated into the genome of said cell line.

By way of preferred examples of such cell lines, one should mention the so called "293 cell line" derived from human embryonal kidney which contains, integrated in its genome, the first 11 % of the 5' region of an Ad5 virus genome. That portion of the Ad5 genome enables recombinant viruses defective in that

region, because of a deletion of part that region, to be appropriately complemented. Such a process for the production of defective viruses has been described more particularly in European patent application n°0185573, filed on November 20, 1985.

After transformation of such cell lines, the defective recombinant viruses are multiplied, recovered and purified.

Needless to say that the same process may be applicable to the production of other defective adenoviruses as a result of a deletion in a region other than in the 5' region referred to hereabove, it being then understood that the cell lines used in such production should then include in their own genome the sequence deleted from the adenoviral genome to thereby allow for the complementation of such defective adenoviruses.

The invention provides thus for the first time a serious alternative to injection in the brain area of cells, e.g. embryonic cells carrying the relevant genetic information, in gene therapy aiming at correcting metabolic deficiencies or defects in the targeted cells, particularly post-mitotic neurons. This is the consequence of the important infective power of adenoviruses, also retained by the corresponding defective adenovirus-derived vectors, of their capacity of spreading throughout the targeted neural or nerve tissue while also remaining substantially confined within the selected tissue, if specifically injected thereinto, as well as of the long-term transcription, and in most instances, expression of the nucleotide sequence carried into the nerve tissue by such adenoviral vectors.

The nucleotide sequence whose introduction in the cells of the central nervous system may be sought, may consist of any sequence capable of providing molecules

interacting with the metabolism of such cells. Such molecules may consist of selected anti-sens RNAs, or anti-sens oligo-ribo-nucleotide, capable of interacting with defective messenger RNAs whose further processing, responsible for corresponding diseases, ought to be blocked, e.g. in a number of neuro-psychiatric diseases, epilepsy, etc... This methodology appears of particular interest in the treatment of the Alzheimer's disease. The anti-sens method could be used, by way of example only, for inducing a blockade of the  $\beta$ -amyloid precursor, for preventing an accumulation of the  $\beta$ -amyloid peptide in the senile plaques. Alternatively use could be made of anti-sens oligonucleotide capable of inhibiting the expression of enzymes involved in the abnormal phosphorylation of proteins, e.g. the TAU protein involved in Alzheimer's disease. Alternatively again the nucleotide sequence is one which could sequester specific binding proteins, themselves normally involved in the processing of the DNA- or RNA-sequence whose transcription or expression is sought to be inhibited.

The nucleotide sequence whose introduction in the cells of the central nervous system may be sought, will more often code for an expression product having a biological property capable of compensating that of a corresponding defective natural polypeptide-containing product encoded by a defective corresponding nucleotide sequence, or of compensating the lack of endogenous production of the natural endogenous corresponding polypeptide containing product in said targeted cells. Examples of such defective polypeptide-containing products may consist of neurotransmitter-synthesizing enzymes and growth factors. For example in the case of Parkinson's disease (which is characterized by a vulnerability of

dopaminergic cells) one could envisage producing locally DOPA or dopamine by expressing the cDNA encoding tyrosine hydroxylase, or a growth factor such as BDNF (brain derived neurotrophic factor) which could favor the survival of dopaminergic neurons.

Likewise for Alzheimer's disease, where one of the missing neurotransmitters is acetylcholine which is synthesized by choline acetyl transferase. Moreover NGF (nerve growth factor) could prevent degeneration of cholinergic neurons.

Another potentially useful factor to express is CNTF (ciliary neurotrophic factor) which could prevent neuron death. But CNTF may also have interesting effect in the brain, e.g. for the blocking of the destruction (seemingly induced in diabetes affected patients) of peripheral nerves. Other trophic factor whose expression may be sought consist, by way of examples of IGF, GMF, aFGF, bFGF, NT3 and NT5.

In a general manner growth factors could be caused to be produced in neuronal cells of patients affected with neuropathies, strokes, spinal cord injury, amyotrophic lateral sclerosis, Huntington's chorea, Alzheimer's and Parkinson's diseases, cerebral palsy. Epilepsia may be, among other possibilities, treated by a local production, in the central nervous system, of the neurotransmitter GABA, as a result of the expression of the glutamic acid decarboxylase.

The invention is also of particular interest for the preparation of compositions for use in the treatment of hereditary diseases affecting the defective or deficient product of the mutant gene: lysosomal enzymes in lysosomal diseases (e.g. hexosaminidases in Tay Sachs and Sandhoff diseases, arylsulfatase in metachromatic leucodystrophy, glucocerebrosidase in Gaucher's disease,  $\beta$ -glucuronidase in mucopolysaccharidosis, HGPRT in

Lesh Nyhan disease, etc...). Hereditary progressive neuron degenerations could be treated by transfer of the normal disease gene via adenoviral vectors, or, as discussed above, by induction of a local production of growth factors. For instance, it has been shown, that production of CNTF could slow down progressive motoneuronal degeneration (pmm) of mice (Sendtner et al, Nature 1992; 358: 502-504), the same being observed with aFGF on photoreceptor degeneration in inherited retinal dystrophy in rat (Faktorovich et al, Nature 1990; 347:83-86). Acquired spinal cord diseases like the frequent and constantly lethal Amyotrophic Lateral Sclerosis (ALS) could perhaps benefit from similar local production of CNTF that has been proved to protect motoneurons.

Inherited dysmyelinating diseases could also be improved by adenovirus-mediated gene transfer into myelin-synthesizing cells.

Finally, some other types of potential therapeutic agents could be locally produced into the CNS, for instance enkephalins to attenuate rebel pains, for instance in cancerous patients.

The invention also relates to the pharmaceutical compositions consisting of the recombinant adenoviral vectors containing the nucleotide sequences as defined above, in association with a pharmaceutical carrier suitable for the administration route to be selected, e.g. direct in situ injection of the viral suspensions obtained in the relevant neural tissue (or though far less preferred, through a general route, e.g. intravenous route, particularly when the adenoviral vector also contains a promoter selectively operative in determined nerve tissue or cells).

The invention is not limited to the therapeutical uses contemplated hereabove, of the adenoviral vectors. The latter can also, owing to their high

infectivity, be used either in in vitro assays on determined populations of neural cells, e.g. for the sake of studying the capacity of a promoter (then coupled to a suitable "marker", e.g.  $\beta$ -gal) of being recognized by the polymerases of said neural cells. Alternatively such adenoviral vectors can also be used for the detection or the evaluation of the interaction recombinant virus (that expressed by the nucleotide sequence under the control of a promoter operative in such cells) with a given population of neural cells or a more complex nerve tissue. For instance that evaluation or detection may aim at localizing those cells of the more complex tissue which carry a receptor for the virus. The detection can make use of any appropriate classical labeled method, e.g. use of labeled antibodies to detect expression products of the nucleotide sequence assayed. The prospects of these evaluations may be considerable in the field of neuroanatomy.

The recombinant vector of this invention is also useful in a method comprising causing the transcription product or expression product of a nucleotide sequence coding for a selected polypeptide to be targeted or produced in cells of the central nervous system, e.g. brain and spinal cord cells, particularly neural, glial or ependymal cells, of an animal and detecting the resulting physiological or behavioral modification induced in said animal by said transcription product or said expression product.

For instance in the case of a lesion of the septohippocampic track which depletes the hippocampus in acetylcholine, it would be possible to study the effects of the transfer of a gene coding for the choline acetyl transferase (ChAT) in the hippocampus. The introduction of that gene in the target core of cholinergic fibers (cut by the lesion) could elicit a

re-increase of the amount of the available acetyl choline and, consequently, correct the deficit. This deficit can be evaluated by behavioral tests of memorization. For instance mice thrown in a "swimming pool" can learn to find again a platform which enables them to escape to water (Morris swimming pool). However the animals whose septo-hippocampic track has been deteriorated are very handicapped in that operation. The detection of an increase of the acetyl choline produced as a result of the gene expression would then be appreciated by the ease with which the animals would be able again to find the platform.

According to another example, the invention would enable the analysis of the degree of compensation of troubles of the motor behavior produced by the denervation of the striatum, particularly in the event of a lesion of the dopaminergic cores of the mesencephale (black substance). The introduction of the gene coding for tyrosine hydroxylase (TH) in the striatum could correct that deficit. The compensation can be evaluated by the study of the behavior of rats in the rotation test: animals wounded on one side only rotate in a repetitive fashion (over ten rotations per minute) when they receive an injection of apomorphine. The production of dopamine (linked to the introduction of the TH gene) could be appreciated in that behavioral test.

Still according to another example, the invention allows for the electrophysiological and behavioral study in other cases. For instance, the neurones of the dorsal horn of the spinal cord which transmit information bound to nociceptive stimulation (pain channels) are sensitive to morphine which causes their activity to be decreased. The introduction of a gene coding for an endomorphine in the spinal cord could provoke a secretion of this substance which, like

morphine, would act of these cells. Such an action could be evaluated by behavioral tests (threshold of reaction of animals to nociceptive stimulation) as well as by electrophysiological studies on the neurones themselves of the spinal cord. Recording of the activity of these cells would enable one to appreciate the existence of a modulation induced by the expression of the transferred gene.

The possibilities afforded by the invention will be further illustrated, yet in a non-limitative manner by the description of a number of assays, which are in part supported by figures appended to the present description. Particularly, the Ad.RSV $\beta$ gal appears as an appealing means to analyze neuronal -and glial-morphology in specific areas of the brain by providing Golgi-like staining of cells at the injection site. Filling up of the axons by the enzyme may additionally provide ways to analyze projections of discrete neuronal populations. Conversely uptake of the virus by the terminals and subsequent retrograde transport to the neuronal cell body allows tracing of sets of afferents to a specific brain area.

One major advantage of this technique for neuroanatomy is the easy combination of the X-gal stain with all sorts of other labeling techniques, in particular immunocytochemistry. The use of vectors in which the nls sequence would be omitted might improve the efficacy of such a technique.

Similarly that adenoviral vector provides a basis for the study of the action of other promoters substituted for the RSV LTR promoter, with respect to different neural cell populations.

Assays 1:

Use has been made of the replication defective adenovirus, the Ad.RSV $\beta$ -gal, which expresses a nuclearly targeted  $\beta$ -galactosidase ( $\beta$ -gal) driven by

the Rous sarcoma virus long terminal repeat (RSV LTR) promoter (9). The SV40 nls (nuclear localization signal) in said vector provided for the targeting of the vector to the nuclei of the cells. The ability of this vector to infect primary cultures of sympathetic neurons of superior cervical ganglia (SCG) and astrocytes was tested. The  $\beta$ -gal activity was visualized histochemically using the chromogenic substrate 5-bromo-4-chloro-3-indolyl- $\beta$ -D-galactosidase (X-gal) (10). SCG cultured in the presence of an antimitotic agent provide a convenient means to obtain a pure and homogeneous preparation of neurons (11).

More particularly expression of  $\beta$ -gal in cultured sympathetic neurons and astrocytes after inoculation by adenovirus Ad.RSV $\beta$ -gal was carried out as follows:

SCG were removed from 2 day-old Wistar rats, dissociated, plated onto 16 mm collagen-coated dishes and cultured as described in (11). Cytosine arabinofuranoside (10  $\mu$ M) was added during the first week of culture to prevent proliferation of ganglionic non-neuronal cells. After 6 days in the culture, cells were inoculated with  $10^6$  plaque-forming units (pfu) of Ad.RSV $\beta$ -gal in culture medium or, as a control, exposed only to culture medium. Twenty-four hours later, the virus was removed and cells were maintained for 2 days in culture medium. Cells were washed, fixed with paraformaldehyde and  $\beta$ -gal activity was then revealed by histochemical staining (10).

After 6 days of culture the following observations were made: virtually all cells were  $\beta$ -gal positive, with no apparent toxic effects or morphological changes. Positively labeled cells could not be detected when the staining reaction was performed in a parallel non-inoculated culture.

The ability of adenovirus to infect primary cultures of rat hippocampal tissue enriched in

astrocytes was tested too. Inoculation resulted in a blue nuclear staining in about two-thirds of the cells. The identification of  $\beta$ -gal positive cells as astrocytes was confirmed by additional staining with an antibody against glial fibrillary acidic protein (GFAP).

More particularly the assays were carried out as follows. Primary enriched astrocyte cultures were established from neonatal rat hippocampal tissue as described elsewhere (12). Cells were plated in 35 mm diameter plastic dishes and grown in supplemented Dubelcco modified Eagle's medium (DMEM) for 5 days. 2  $\mu$ l of the adenoviral solution (titer  $10^8$  pfu/ml) were then inoculated in each dish for 24 hours. After washing and paraformaldehyde fixation, cells expressing  $\beta$ -gal were characterized using X-gal histochemistry. A superposition of the two labels was observed (not represented).

#### Assays 2:

The feasibility of adenovirus to infect brain cells in vivo was evaluated in number of characteristic structures.

Seventeen male Wistar rats (10 week-old) were stereotactically injected under deep anesthesia with 1 to 5  $\mu$ l of media containing  $10^{10}$  plaque-forming units (pfu)/ml of highly purified virus into either the hippocampus or the substantia nigra. Animals were sacrificed at 1, 2, 3, 5, 7, 30 and 60 days after inoculation.  $\beta$ -gal activity in positive cells was detected histochemically by using both the X-gal substrate, and an antibody directed against the protein (antibody was an affinity-purified rabbit IgG fraction to  $\beta$ -gal (Cappel, 1:800 dilution) which was then bound with a streptavidin-biotinylated peroxidase complex (Amersham) with diaminobenzidine as a chromogen, reinforced with nickel). The latter method

is more sensitive and in some instances revealed  $\beta$ -gal in fine cytoplasmic processes due to high expression of the transferred gene.

All injected animals displayed a high level of  $\beta$ -gal activity. The expression was detected as early as 24 hours after inoculation and persisted in animals analysed after two months. The diffusion of the virus was greater in the hippocampus than in the substantia nigra and it spread through the entire dorsal hippocampus. In the substantia nigra, the overall pattern of infection was more restricted and distributed along a medio-lateral orientation. This difference may likely reflect the propensity of the virus to spread through tissues with a low adhesivity, such as the hippocampal fissure and the boundaries between the granule cell layer of the dentate gyrus and surrounding tissues.

In the hippocampus, the extent of the infected area was correlated with the volume of viral solution administered. Typically, in rats sacrificed 3 to 7 days after hippocampal inoculation, the infected area ranged from 1 to 4  $\text{mm}^3$  for 3-5  $\mu\text{l}$  injected virus ( $10^{10}$  pfu/ml). Interestingly, a careful examination of the hippocampal sections over time, revealed a change in the pattern of labeling. While only minor differences were noticed within the first week post inoculation, a remarkable remodeling in the distribution of labeled cells was observed after one month. This new pattern was maintained after two months. In this long-term pattern, the distribution of  $\beta$ -gal positive cells was less diffuse, the labeling appeared to be confined to a defined cell layer.

No apparent cytotoxic effect was observed in the infected animals. All survived the inoculation without any noticeable behavioral abnormalities. Examination of the virus-infected brains revealed no enlargement of the lateral ventricle, nor disruption of the normal

cytoarchitecture of the structures. The only noticeable alteration was a local tissue necrosis and reactive gliosis, which was restricted to the injected site. This phenomenon was largely due to the injection itself since a similar effect was observed in animals injected with saline. Finally, analysis of hippocampal sections at a cellular level with Nissl staining showed no cell loss nor evidence of cytolysis within the pyramidal cell layers or the granule cell layer of the dentate gyrus.

Assays 3:

The preceding results establish that the adenovirus can infect brain cells. The following experiment establishes more particularly that neurons can be infected in vivo.

Glial and neuronal cell types were infected by direct in vivo inoculation of the adenovirus Ad.RSV $\beta$ -gal. The  $\beta$ -gal expression in microglial cells was made by immunohistochemical detection near the injected area of a rat which received intrahippocampal injection 5 days before sacrifice. Immunohistochemical reaction was processed using peroxidase reinforced with nickel and with fluorescein conjugated secondary antibody.

Shortly after injection many of the  $\beta$ -gal positive cells exhibited a morphology typical of microglial cells. These small cells display fine, highly branched processes extending radially away from the cell body. Although microglial cells represented a large proportion of  $\beta$ -gal expressing cells up to one week, their numbers decreased drastically at longer post-infection times. Other infected cells detected during the early time points were demonstrated to be astrocytes by double staining using the X-gal substrate and an antibody directed against the

astroglial glial fibrillary acidic protein (GFAP) (data not shown).

Compelling evidence that some of the infected cells are neurons was established for both injected cerebral structures. In the case of the substantia nigra, the presence of  $\beta$ -gal in dopaminergic cells could be documented using an antibody directed against tyrosine hydroxylase (TH), a classical marker of catecholaminergic neurons. Higher magnification clearly revealed that cells marked with TH antibodies also exhibited a blue nucleus. These cells account for about 50 % of the  $\beta$ -gal positive cells within the infected dopaminergic cell area. In the hippocampus, numerous labelled cells were unambiguously identified as neurons based on both morphological and anatomical characteristics (Fig. 1). In some cells, the staining revealed a Golgi-like profile due to the diffusion of  $\beta$ -gal, resulting from high level of expression of the enzyme. This pattern was observed mostly from 48 hours to one week. Pyramidal neurons, granule cells and hilar interneurons were seen in the pyramidal cell layer CA1, the granule cell layer and the hilus of the dentate gyrus. These latter cells could easily be identified because of the characteristic cytoarchitecture of the hippocampus which is composed of distinctly segregated and laminated cellular subgroups. Occasionally, long stained processes were observed at distances greater than 400  $\mu$ m from the cell body, confirming the neuronal nature of these cells. In addition, several segments with giant varicosities were seen running through the hilus, indicating that mossy fibers were also labelled.

As pointed out above, in all the rats sacrificed at one or two months after inoculation, the distribution and number of positive  $\beta$ -gal cells are markedly different from that observed at earlier time

points. The distribution of  $\beta$ -gal positive cells was evaluated in the dentate gyrus one month after Ad. RSV $\beta$ -gal adenoviral inoculation, using X-gal histochemistry. The blue labeled cells were found to be concentrated in the left dentate gyrus of the injected hippocampus, as compared to non-injected contralateral side (Fig. 2 Scale bar, 1 mm). Dentate localization of infected cells was confirmed by immunohistochemical  $\beta$ -gal detection (staining using peroxidase plus nickel). A high magnification (40x) view shows the great number and densely packed  $\beta$ -gal labeled cell nuclei in the granule cell layer of the dentate gyrus (Fig. 3 Scale bar, 300  $\mu$ m).

The molecular layer, which was highly infected at shorter post-inoculation times, was then devoid of stained cells. As detected in sections counterstained with cresyl violet (data not shown),  $\beta$ -gal positive cells coincided with that of the granular layer and no positive cells were seen in the innermost part of the layer which includes most of the basket cells and a few glial cells. The blue staining in the rat sacrificed after two months was exclusively concentrated in the granule cell layer.

#### Assays 4:

The high level of neural cell infectability by the adenovirus is further demonstrated by the results of the experiments reported hereafter.

#### Methods:

Adenovirus vectors containing the LacZ gene were prepared according to procedures described previously (5). Thirteen adult Sprague-Dawley rats (Charles River France) were anesthetized using chloral hydrate (400 mg/kg, i.p.) and placed in a stereotactic apparatus. A viral suspension containing  $3.3 \times 10^{10}$  to  $10^{11}$  plaque forming units (pfu) per ml was injected over ten minutes using a Hamilton syringe (10  $\mu$ l,

total injection:  $3.3 \times 10^8$  to  $10^9$  pfu) into the XIIth nucleus (n=6) or into various regions of the forebrain (n=7). After four days survival time, rats were reanesthetized and perfused transcardially with 4 % paraformaldehyde in phosphate buffer (0.1 M; pH 7.4). The central nervous system was removed, post-fixed for 4 hours then cryoprotected overnight in 30 % sucrose. Parasagittal sections (48  $\mu$ m-thickness) were cut on a cryostat. Every fourth section was incubated for 4 to 12 hours at 28-30°C with the X-gal stain as described previously (10). In three rats, X-gal treated sections were rinsed in phosphate buffer then further treated using classical immunohistochemical techniques with Vectastain kits (Vector labs) using either a rabbit polyclonal antibody raised against GFAP (1/500) or the mouse monoclonal antibody OX-42 (1/1200) that specifically stains microglial cells in the rat central nervous system. Sections were then mounted on gelatinized slides and every other section was counterstained with cresyl violet before final coverslipping from toluene.

Figure 4 provides photomicrographs showing  $\beta$ -galactosidase histochemical staining in various cell populations in the rat brain after the above said adenovirus injection a. and b. labeling observed after injection into the nucleus of the twelfth nerve (XII). Virtually all the neurons in the XII nucleus have been infected, staining extending in all neuronal processes including axons (arrow in a.), providing a "Golgi-like" appearance of the cells. Some of the infected cells can be identified as astrocytes (arrowheads) by the brown reaction product indicating immunoreactivity for GFAP (glial fibrillary acidic protein). d., Staining in ependymal cells (ep) following a intra-ventricular injection. Sections in a, b and d have been counterstained with cresyl violet.

The following observations were made.

No gross adverse effect of this inoculation on the animals' health and behavior was observed up to 60 days after inoculation (the longest time studied). In all cases, a large number of cells were histochemically stained. Neural cells were infected including neurons (Figs 4a,b) and glia identified as astrocytes (Fig. 4c) or microglia (not shown) in double-staining experiments using specific immunocytochemical markers. When injections were aimed at the ventricular system, a wealth of ependymal cells expressed the gene (Fig. 4d).

In the brain parenchyma, labeled cells were mostly found within 500 to 1000  $\mu\text{m}$  from the needle track. Borders of the area containing infected cells tended to respect anatomical boundaries such as large fiber tracts or lamellae. For example, injections aimed at the nucleus of the XIIth nerve (Fig. 4a,b) produced virtually a complete and intense staining of all neurons within the nucleus while surrounding areas contained only scattered infected cells. Similarly, injected ependymal cells were observed over several millimeters after intraventricular injections, while adjoining neural tissue did not contain any stained cells (Fig. 4d). It is likely, therefore, that the topography of  $\beta$ -galactosidase expressing cells at the injection site corresponds to a limited spread of viral particles within the tissue and that anatomical boundaries such as large fiber tracts or the glia limitans prevent their diffusion.

Assays 5:

In addition to cells labeled around the needle track, for which endocytosis of viral particles at the perikaryal level was likely, remote groups of neurons that send axonal projections to the area of injection

were labeled, such as nigral neurons after injection into the striatum (Fig. 5b).

As a matter of fact Fig. 6 represents photomicrographs showing  $\beta$ -galactosidase histochemical staining following adenovirus injection into the striatum. Methods were the same as in Assay 4. a. Reaction product in cells at the periphery of the injection site. Reaction product is mostly in the nuclear-perinuclear region and intensity ranged from very faint (arrowheads) to strong, extending into neurons in the substantia nigra (SN) and in the ventral tegmental area (VTA) that have transported the viral vectors retrogradely from the striatum. x20.

The nuclear-perinuclear localization of the staining in nigral cells as well as the lack of a profuse staining in the nigro-striatal axonal pathway indicates that the viral particles rather than the enzyme was taken up by axonal terminals and transported retrogradely from the striatum to the substantia nigra. In contrast, no histochemical staining was observed in neurons that have axons crossing (but not ending in) the injection site, suggesting that viral particles cannot be endocytosed by axons of passage.

#### Assays 6:

These above results underline the high level of neural cell infectability by the adenovirus. This has also been shown in the assays carried out as follows:

**Methods:** The  $3.3 \times 10^{10}$  pfu/ml suspension was either used directly or diluted using sterile saline before injection into the brain of 10 rats. Other methods are as described in Assays 4 except that sections were cut in the coronal plane.

Photomicrographs showing results obtained one week after injection into the thalamus of adenovirus suspension at different dilutions (sections

counterstained with cresyl violet). a. Cytolytic effect observed after injection of 10  $\mu$ l of a  $3.3 \times 10^{10}$  pfu/ml suspension of viruses (total:  $3.3 \times 10^8$  pfu). Tissue loss and gliotic areas (arrows reveal cell death induced by the viral injection. x20. (section not treated with X-gal). b. Staining after injection of a total of  $3.3 \times 10^5$  pfu. Several thousand cells still expressed the gene, exhibiting mostly nuclear-perinuclear staining except for a few short neurites (arrowhead). There was no conspicuous cytolytic effect. x200. c. Staining after injection of  $3.3 \times 10^3$  pfu. A few cells still expressed the gene (arrowheads) in a small area corresponding to the tip of the needle track. There was no apparent cytolytic effect. x400.

Considerable numbers of cells were infected after inoculation with high titer virus suspensions, but many cells were also infected when much lower titers were used. In rats injected with a 10  $\mu$ l suspension titering  $3.3 \times 10^7$  pfu/ml (a maximum of  $3.3 \times 10^5$  infectious particles) several thousand neural cells still expressed the lacZ gene 8 days after inoculation (Fig. 6b); injections as low as 3,300 pfu resulted in labeling of close to a hundred cells (Fig. 6c). Intensity of labeling was another indication of the exquisite infectability of neural cells. When high titer virus suspensions were used (over  $10^9$  pfu/ml) staining intensity was usually very strong in the center area of the injection site where cells are subjected to the highest viral particle concentration. In spite of the nls sequence added to  $\beta$ -galactosidase, labeling was so intense that it was not limited to nuclei of individual cells, but diffused to cytoplasm and processes (e.g. dendrites and axons of neurons) producing a complete "Golgi-like" staining of the cells (Fig. 6a,b and Fig. 5a). In contrast, in most cells located at the periphery of the injection site

and in retrogradely infected cells, only the nuclei were labeled (Fig. 5a,b). Similarly, nuclear localization of the enzyme was the rule when lower titer virus suspensions were used (Fig. 6b,c).

A single neural cell, in particular a neuron, can thus endocytose a massive amount of viral particles. This high infectability most likely explains the cytopathogenicity (characterized by neuronal death, gliosis, vascular inflammatory response and tissue loss) observed at the site of injection of high titer suspensions (Fig. 6a). The absence of apparent cytopathogenicity of lower titer virus suspensions ( $\leq 10^7$  pfu/ml) supports this hypothesis. Cytopathogenicity most likely relates, therefore, to the endocytosis of enormous numbers of viral particles by cells located close to the injection site.

Assays 7:

Adenovirus infection is clearly not systematically cytopathic, however, since well preserved neural cells expressing the lacZ gene were still observed 45 days after inoculation (Fig 7). Nine rats were injected and sacrificed ( $n=3$ ) every other week after injection. Surgical and histological methods as described in Figure 4 except that sections were cut in the coronal plane. Photomicrographs showing  $\beta$ -galactosidase histochemical reaction product in a rat that was allowed to survive for forty-five days after adenovirus injection into the nucleus of the XIIth nerve (XII). A few cells still expressed the gene as demonstrated by nuclear-perinuclear histochemical staining. Among them were motoneurons as exemplified in the inset (counterstained with cresyl violet). A few axons also contained the enzyme (arrow).  $\times 40$ , inset  $\times 1000$ .

These results demonstrate that cells in the central nervous system, including neurons, can be successfully injected in large numbers by a replication-deficient adenovirus and consequently express a transferred foreign gene.

The impact on gene therapy may thus be considerable. Although as mentioned above the invention aims at providing an alternative to the grafting in the patient whose cells carry a genetic defect of full neural cells containing the nucleic sequence aiming at compensating said genetic defect, particularly from an embryo, it should be understood that it may even further find a use in an improvement of such grafting techniques. Particularly the cells to be grafted could be "enriched" in or provided with the required nucleic sequence by in vitro transformation with an adenoviral vector containing that nucleic sequence, prior to be grafted according to the techniques already of use in cellular therapies. This improvement may be of particular significance in the case of primary cultures of neurons which do not undergo divisions.

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## C L A I M S

1. A recombinant DNA vector characterized in that it is capable of directing the expression an/or transcription of a selected nucleotide sequence in the cells of the central nervous system and in that it comprises (i) at least part of the genome of an adenovirus, including the regions required for that adenovirus to penetrate into the cells normally infectable by that adenovirus and (ii) said selected nucleotide sequence being inserted into said part of genome of an adenovirus under the control of a promoter, either present or also inserted into said genome part and operative in said cells.

2. The vector of claim 1, wherein said recombinant vector is a defective adenovirus, which preferably also includes all of the sequences of the adenoviral genome which are required for the encapsidation of the adenovirus in cells infected by such adenovirus.

3. The vector of claim 1 or 2, wherein said recombinant vector is devoid of the E1A and E1B regions and, optionally, of the region E3 of the adenovirus genome.

4. The vector of any of claims 1 to 3, wherein said promoter is exogenous with respect to the adenoviral genome.

5. The vector of any of claims 1 to 3, wherein said promoter is a neuronal, glial, or ependymal promoter.

6. The vector of any one of claims 1 to 5, wherein said nucleotide sequence under the control of above said promoter codes either for a neurotransmitter or neurotransmitter-synthesizing enzyme or a part of said neurotransmitter or

neurotransmitter-synthesizing enzyme having the biological activity of said neurotransmitter or neurotransmitter-synthesizing enzyme.

7. The vector according of any one of claims 1 to 5, wherein the nucleotide sequence under the control of above said promoter codes for a precursor of a neurotransmitter or a part of said precursor having the biological activity of said precursor.

8. The vector of any one of claims 1 to 5, wherein the nucleotide sequence under the control of the promoter codes for a trophic factor or for part thereof but having the biological activity of said trophic factor.

9. The vector of any one of claims 1 to 5, wherein the nucleotide sequence under the control of the promoter codes for a growth factor or a part of said growth factor but having the properties of that growth factor.

10. The vector of any one of claims 1 to 5 wherein the nucleotide sequence under the control of the promoter is an antisense sequence.

11. The vector of claim 10, wherein the nucleotide sequence under the control of the promoter is an antisense sequence whose transcription product is capable of blocking the expression of toxic proteins (i.e. prions, kinases, proteins TAU,  $\beta$ -amyloid, etc...) or of enzymes involved in the biosynthesis of said toxic proteins or of glutamate.

12. A process for the production of a recombinant vector useful in a method comprising causing the transcription product or expression product of a selected nucleotide sequence to be targeted or produced in cells of the central nervous system, e.g. brain and spinal cord cells, particularly neural, glial or ependymal cells, wherein said recombinant vector is an adenoviral vector which

comprises at least part of the genome of an adenovirus including at least those regions of that genome which provide the genetic information required by that adenovirus to penetrate into cells normally infectable by it and, said nucleotide sequence being inserted in said genome part, under the control of a promoter, either present or also inserted within said adenoviral vector, said promoter being operative in said cells.

13. The process of claim 12, which is a vector according to any of claims 2 to 11.

14. The process of claim 12 or 13, for the production of a recombinant vector useful in a method comprising causing in an animal the transcription product or expression product of a selected nucleotide sequence to be targeted or produced in cells of its central nervous system, e.g. brain and spinal cord cells, particularly neural, glial or ependymal cells, and detecting the resulting physiological or behavioral modification induced in said animal by said transcription product or said expression product.

15. The process of any of claims 12 to 14, for the production of a recombinant vector for use in the treatment of disorders of the central nervous system.

16. The process of claim 15, for the production of a recombinant vector useful in a method for gene therapy and wherein the nucleotide sequence under the control of said promoter is an exogenous sequence capable of compensating a corresponding deficient or defective nucleotide sequence in said cells of the central nervous system.

17. The process of claim 15 or 16, wherein said nucleotide sequence under the control of said promoter is capable of being transcribed in an anti-sens RNA or anti-sens oligonucleotide capable of interacting with a selected messenger RNA.

18. The process of claim 15 or 16, wherein said nucleotide sequence under the control of said promoter is capable of being expressed in the form of an expression product having a biological property capable of compensating that of a corresponding defective natural polypeptide-containing product encoded by a defective corresponding nucleotide sequence or the lack of endogenous production of the natural endogenous corresponding polypeptide-containing product in said targeted cells.

19. A pharmaceutical composition containing a recombinant adenoviral vector as defined in any one of claims 1 to 11, in association with a pharmaceutical vehicle allowing its administration to human or animal, for the treatment of disorders of the central nervous system.

20. A method for the detection of the effectiveness or operativeness of a promoter in part or all of the cells of a population of neural cells, which comprises:

- infecting said population with a recombinant adenoviral vector including those regions of the corresponding adenovirus which provides the genetic information required by that adenovirus to penetrate into cells normally infectable by it, and which further contains a nucleotide sequence coding for a marker inserted in a region of said adenovirus, wherein said promoter has also been inserted by means of a genetic construction in said recombinant adenoviral vector such as to have said nucleotide sequence be placed under its control,
- and detecting those cells among said population in which expression of the marker has taken place.

21. An animal pathological model comprising a non-human animal whose nervous cells or at least some of them contain a vector according to any one of claims 1 to 11, which has been introduced into said animal or an ancestor of said animal.

22. An animal pathological model according to claim 21 which is a model for neurodegenerative diseases.

23. A process for the production of a recombinant polypeptide comprising the culture of nervous cells containing a vector according to any one of claims 1 to 11, whose selected nucleotide sequence encodes said polypeptide.

24. A population of cells of the central nervous system, e.g. brain and spinal cord cells, particularly of neural, glial or ependymal cells, respectively transformed with a recombinant DNA vector as defined in any of claims 1 to 11.

25. The population of cells of claim 24, which is in a form suitable for grafting in the host, particularly form which (or whom) these cells were initially obtained.

26. A process for the production of a protein or polypeptide of therapeutical value which comprises cultivating a population of cells as defined in claim 24 in which the nucleotide sequence of interest codes for that protein or polypeptide.

27. The process of claim 26 wherein said nucleotide sequence is as defined in any of claims 6 to 9.

A B S T R A C T

**ADENOVIRUS VECTORS FOR THE TRANSFER FOREIGN GENES INTO  
CELLS OF THE CENTRAL NERVOUS SYSTEM, PARTICULARLY IN  
BRAIN**

The invention concerns a recombinant DNA vector characterized in that it is capable of directing the expression an/or transcription of a selected nucleotide sequence in the cells of the central nervous system and in that it comprises (i) at least part of the genome of an adenovirus, including the regions required for that adenovirus to penetrate into the cells normally infectable by that adenovirus and (ii) being inserted into said part of genome of an adenovirus under the control of a promoter, either present or also inserted into said genome part and operative in said cells. This recombinant vector finds particular use in the treatment of diseases of the central nervous system, also in gene therapy.

No drawing

FIGURE 1



2 / 8

FIGURE 2



3 / 8

FIGURE 3

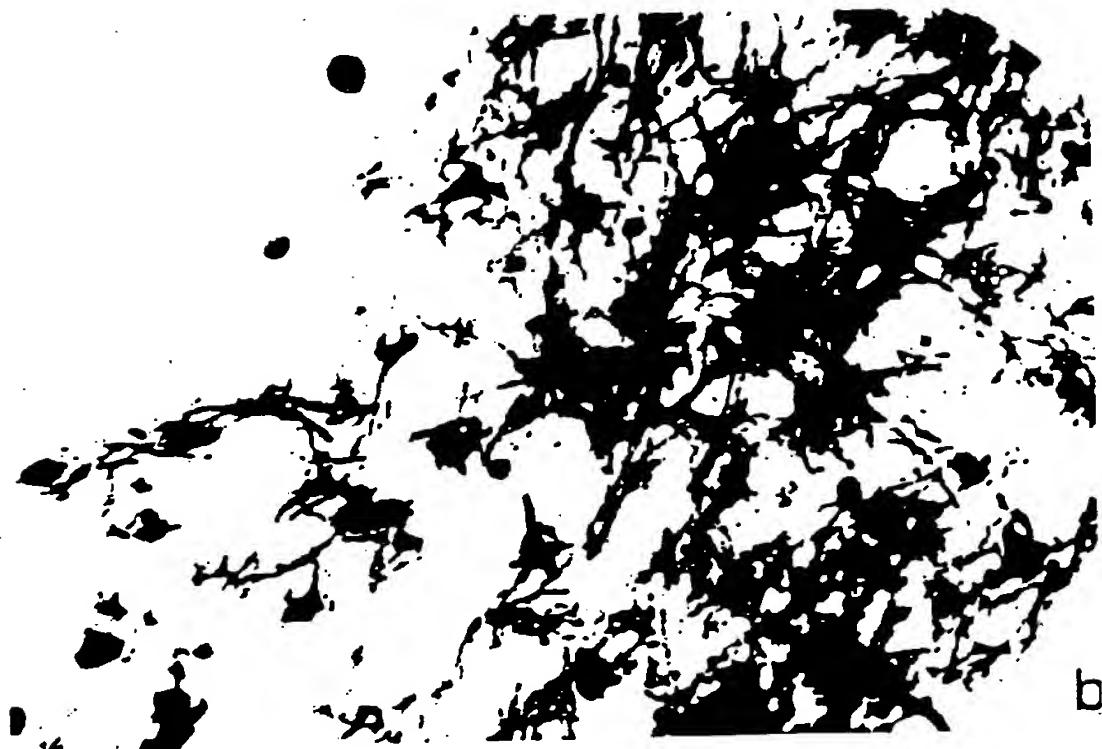


4 / 8

FIGURE 4



a



b

5 / 8

FIGURE 4 (suite)



ep

d

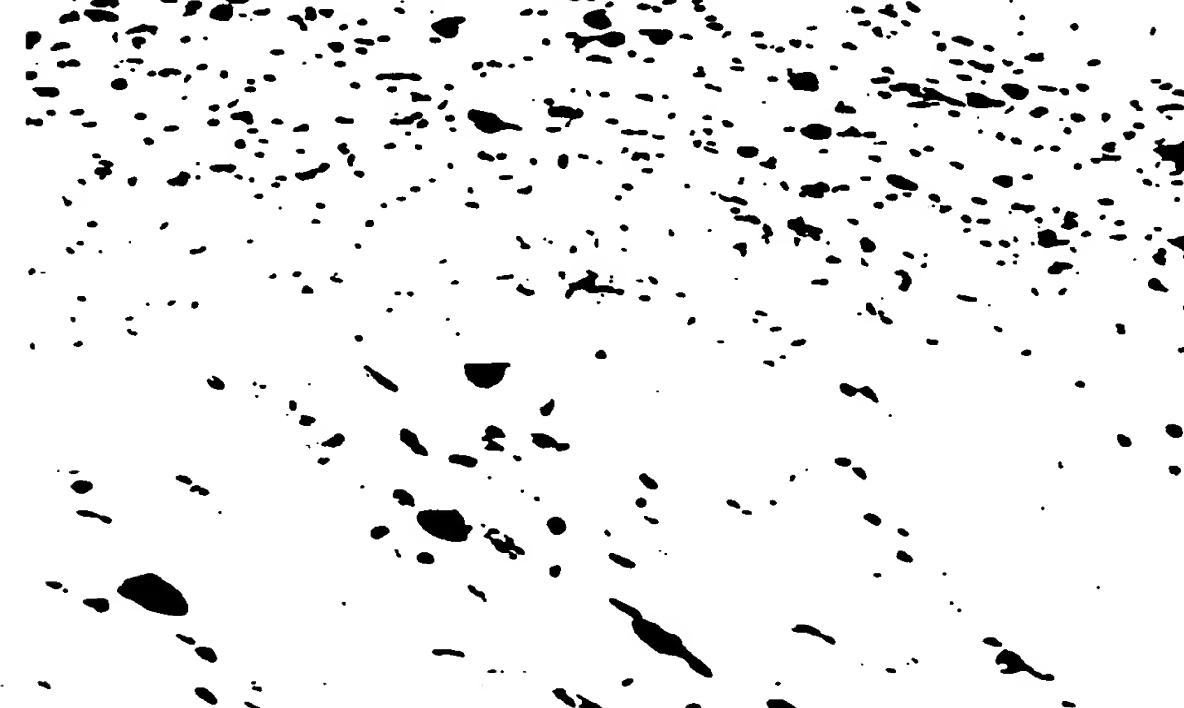
6 / 8

FIGURE 5



7 / 8

FIGURE 6



8 / 8

FIGURE 7



